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Existence of ${}^{4}_{\Lambda\Lambda}$H and Decay to a Resonance in ${}^{4}_{\Lambda}$He

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Abstract

Experiment $E906$ at the BNL-AGS, searching for light $S = -2$ hypernuclei, found strong evidence for the nuclide ${}_{\Lambda\Lambda}^{4}$H. Perhaps the most striking feature of this experiment was the presence in the data of a narrow low-momentum π^- line at $k_\pi = 104-105$ MeV/c. This line was ascribed to the decay of ${}_{\Lambda\Lambda}^{4}$H into a resonant state in ${}^{4}_{\Lambda}$He. The existence of such a state is shown to be plausible, its characteristics delineated, and its relevance to ongoing theoretical calculations considered.

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Unlike the traditonal emulsion experiments [1–3], the BNL-AGS experiment E906 [4], a counter experiment looking for correlated two π^- decays, was able to accumulate several tens of plausible samples of the hypernucleus ${}_{\Lambda\Lambda}^{4}$H. In this work we concentrate [5] on one of the prominent decay modes of this nuclide, ascribed [4, 6] to initial decay into a resonant state in ${}_{\Lambda}^{4}$He. This is in analogy to the well-known decay of ${}_{\Lambda}^{5}$He which gives rise to a rather narrow peak in the π^- spectrum [7]. A major part of our motivation is to present a more detailed discussion of the ideas that went into the interpretation of E906 [4]. We conclude that this peak very straightforwardly arises as a resonance in a potential limited in the first instance to obtaining the correct ground state energy for ${}_{\Lambda}^{4}$He; a *common* potential with reasonable shape and radius accounts for both states.

One expects the major sequential decays of ${}_{\Lambda\Lambda}^{4}$H to be:

$$
\begin{aligned}
{}_{\Lambda\Lambda}^{4}\mathrm{H} &\rightarrow {}_{\Lambda}^{4}\mathrm{He} + \pi_H^- \qquad (\sim 112 - 118 \text{ MeV/c}) &(1)\\
{}_{\Lambda}^{4}\mathrm{He} &\rightarrow {}^{3}\mathrm{H} + p + \pi_L^- \quad (\sim 85 - 95 \text{ MeV/c}) &(2)
\end{aligned}
$$

and in particular, a decay into a possible excited state of ${}_{\Lambda}^{4}$He,

$$
\begin{aligned}
{}_{\Lambda\Lambda}^{4}\mathrm{H} &\rightarrow {}_{\Lambda}^{4}\mathrm{He}^* + \pi_L^- \quad (\sim 104 - 105 \text{ MeV/c}) &(3)\\
{}_{\Lambda}^{4}\mathrm{He}^* &\rightarrow {}_{\Lambda}^{3}\mathrm{H} + p &(4)\\
{}_{\Lambda}^{3}\mathrm{H} &\rightarrow {}^{3}\mathrm{He} + \pi_H^- \qquad (114.3 \text{ MeV/c}), &(5)
\end{aligned}
$$

where π_H^- and π_L^- refer to the high and low momentum members of a correlated pair seen in the experiment.

The resonance depicted in Eqs. (3-4), as indicated below, would certainly be suppressed in a standard single hypernucleus search, e .g. ${}^{4}\mathrm{He}(K^-, \pi^-){}_{\Lambda}^{4}\mathrm{He}$ [8], but plays a dominant role in E906 , seemingly the only explanation [4] for the strong π^- decay line seen at $104 - 105$ MeV/c. We identify a candidate, not surprisingly a (proton + ${}_{\Lambda}^{3}$H) relative p state, and establish its suitability. A state of this architecture would lead directly via the decay of ${}_{\Lambda}^{3}$H, to the higher momentum π^- decay line at 113-116 MeV/c correlated with the considerably narrower feature at $104 - 105$ MeV/c in the E906 data [4].

This $104 - 105$ MeV/c line [9] has the characteristics of a conspicuous daughter for the decay mode cited abve. One can construct simple non-spurious $1\hbar\omega$ shell-model states which should be populated strongly in the π^- decay of ${}_{\Lambda\Lambda}^{4}$H, and themselves decay via proton rather than Λ emission. Ideally one might attempt to treat the 4-body nature of the ${}_{\Lambda\Lambda}^{4}$H and ${}_{\Lambda}^{4}$He systems [9–13]. Since even the $S = -1$ baryon-baryon foces are by no means uniquely defined, establishing the presence of a weakly bound, or in particular a low-lying resonant, state is a daunting theoretical task. Calculations [14, 15] for ${}_{\Lambda}^{3}$H indicate that ΛN-ΣN coupling must be included. Ultimately, it is precisely the experimental evidence considered here and elsewhere that should constrain and illuminate hypernuclear few-body theory.

At present reasonable evidence exists for such a state from experiment [4]. The dynamics of an essentially (p + ${}_{\Lambda}^{3}$H) p-state can be approximated by a one body + cluster potential problem. The effective interaction between a proton and a three particle hyperon core can be viewed as the average potential arising *after* a many-body treatment. The most relevant information, the basic s-wave to p-wave separation is very much an effective single-particle property. That the anticipated resonance emerges naturally from such modeling is strogly suggestive.

The characteristics of such a potential are fairly clear, one is dealing with rather spatially extended systems for both the weakly bound ${}_{\Lambda\Lambda}^{4}$H and resonant ${}_{\Lambda}^{4}$He*. Moreover, the potential can be strongly constrained, by the requirement that its depth also accommodate the ground state of ${}_{\Lambda}^{4}$He. The spatial extension suggests one might use a potential with a relatively large radius, or even a surface potential. The resulting spatially extent also favors the decay into the resonance in Eq. (3) from the expected weakly bound ${}_{\Lambda\Lambda}^{4}$H.

To help pick out possible candidates for the negative-parity resonance in ${}_{\Lambda}^{4}$He, and to illustrate important features of the π^- weak decay of ${}_{\Lambda\Lambda}^{4}$H, we enumerate in Eqs. (6)-(8) the possible $1\hbar\omega$, $T = 1/2$, states in an harmonic oscillator shell-model basis with $\hbar\omega_N = \hbar\omega_\Lambda$. The oscillator structure, with inappropriate radial wave functions (not actually used here) for loosely bound systems, nevertheless has the virtue that spurious center of mass states can be eliminated, as in Eq. (6), and the explicit intrinsic-spin structure of the states makes it clear which states can be fed strongly in the π^- weak decay of ${}_{\Lambda\Lambda}^{4}$H.

$$\sqrt{\frac{\mu}{3+\mu}}\;(s^2p)[3]1/2 \times s_\Lambda \;-\; \sqrt{\frac{3}{3+\mu}}\;s^3 \times p_\Lambda \tag{6}$$

$$(s^2p)[21]1/2 \times s_\Lambda \tag{7}$$

$$(s^2p)[21]3/2 \times s_\Lambda \tag{8}$$

Here $\mu = m_\Lambda/m_N$ and $[f]S_{3N}$ labels the spatial symmetry and intrinsic spin of the three

Final state	${}^{4}_{\Lambda}$He(1^+)	Eq. (6)	Eq. (7)	Eq. (8)
Production	1	$\mu/(3+\mu)$	1	4
${}^{4}_{\Lambda}$He(1^+)	1			
^{3}He+Λ		1		
${}^{3}_{\Lambda}$H+p			1/9	8/9
$d+p+\Lambda$			8/9	1/9

TABLE I: Matrix elements for the production of single-Λ hypernuclear configurations in the π^- weak decay of ${}_{\Lambda\Lambda}^{\ 4}$H are given in the first row in units of $s_{\pi^-}^2 \left\langle l_N | j_{l_N}(k_\pi r) | s_\Lambda \right\rangle^2 / 4\pi$ where $\mu/(3+\mu) = 0.284$. The remaining rows specify the breakup of the single-Λ hypernuclear configurations under the assumptions described in the text. Combining production and decay in this simple approach shows that ${}^{3}_{\Lambda}$H+p is favored over $d+p+\Lambda$ by a factor of 11/3 to 4/3.

nucleons. For each of the three classes of states $L=1$ and two values of total intrinsic spin S are possible. In the same model, the ${}_{\Lambda\Lambda}^{\ 4}$H initial state is simply $s^2(1) \times s_\Lambda^2(0)$ with $S=1$. Because the dominant piece of the weak-decay operator does not involve intrinsic spin, only ${}^{4}_{\Lambda}$He states with $L=1$, $S=1$, and $J=0,1,2$ are considered.

Because the proton threshold in ${}^{4}_{\Lambda}$He at 7.75 MeV is much higher than the Λ threshold at 2.39 MeV any state with even a rather small p_Λ component will decay predominantly to ^{3}He+Λ. This rules out the states of Eq. (6), although such states could be fed via the s_Λ component in the weak decay leading to a ^{3}He+Λ final state. The states in Eqs. (7) and (8), which should be at similar excitation energies, qualify as candidates provided that admixtures of the states of Eq. (6) are small enough to keep the Λ width comparable to or less than the proton width. The condition for this to be the case is that the off-diagonal matrix elements are sufficiently small relative to the difference in diagonal energies, as demonstrated in Ref. [5].

Relevant analogies exist in light nuclei, with a number of narrow states present at high excitation energies because of the symmetry structure of the wave functions, e.g. a $3/2^+$ state of $t+d$ structure at 16.75 MeV, in ^{5}He and an analogous state in ^{5}Li despite a large decay energy into the $\alpha+N$ channel.

If the intrinsic spins in the configurations in Eqs. (7) and (8) are recoupled to the form $(s^2 s_\Lambda) S_{3H} \times p$, $S_{3H} = 1/2$ is required for the ${}^{3}_{\Lambda}$H+p channel; $S_{3H} = 3/2$ leads to the $d+\Lambda+p$

final state. In fact, the configuration in Eq. (8) dominates the $S_{3H} = 1/2$ strength. This discussion of the possible decay channels of ${}_{\Lambda\Lambda}^{4}$H is summarized in rows $2-5$ of Table 1.

We reproduce the essential features of Kumagai-Fuse and Okabe [9] using just the dominant piece of the weak-decay operator which does not involve the nucleon spin. The widths that they calculate for decays to ${}_{\Lambda}^{4}$He(1^+) and to ${}_{\Lambda}^{3}$H+p are 0.68 and 0.80 Γ_Λ,respectively. In the plane-wave limit for the outgoing π^- the operator is simply $s_{\pi^-} j_\lambda(k_\pi r) Y_\lambda$, where s_{π^-} is a strength known from the decay of the free Λ. The squares of the matrix elements of this operator, taking into account the usual statistical weighting, appear in the first row of Table 1. The complete calculation [5] leads to a rate to the resonant candidates at ~ 8.9 MeV comparable to that for the ${}_{\Lambda}^{4}$He(1^+) state. ${}_{\Lambda}^{3}$H should be produced sufficiently that the scenario [4] put forward in Eqs. (3), (4), and (5) is reasonable.

We now construct a potential to represent the average interaction between the proton and an effective ${}_{\Lambda}^{3}$H cluster in both ground and resonant states of ${}_{\Lambda}^{4}$He. We employ a resonance code due to T. Vertse, K. F. Pal and Z. Balogh [16] to perform the necessary calculations, with a surface Saxon-Woods potential, with radius R and diffusivity a:

$$V^{Surf}(r) = -V_0 \left[\frac{4e^{(r-R)/a}}{(1+e^{(r-R)/a})^2} \right] . \tag{9}$$

Only the strength of the surface potential component is varied and reproduces the correct 7.75 MeV separation energy with a depth $V_0 = 28.09$ MeV, radius parameter $R = 2.07$ fm, and diffusivity $a = 0.5$ fm. In this completely specified well, the p-wave resonance appears at $\epsilon = 1.18$ MeV with a width of 1.00 MeV. Both these numbers are consistent with the observed narrow π^- line at $104 - 106$ MeV/c in E906. Most convincing in this analysis is the ease with which the ${}_{\Lambda}^{4}$He resonance is extracted, once the ground state binding of the proton is assigned.

Given the resonance energy, the $\Lambda\Lambda$ pairing energy $\Delta \mathrm{B}_{\Lambda\Lambda}$ can be estimated from the position of the narrow π^- peak ascribed to the weak decay from ${}_{\Lambda\Lambda}^{4}$H to ${}_{\Lambda}^{4}$He*. The π^- momentum k^* is to a good approximation in the region of momentum considered here,

$$k^*_\pi = (107.466 - 1.6391\Delta) \text{ MeV/c}, \tag{10}$$

where $\Delta = \mathrm{B}^* + \epsilon_R$ and $\mathrm{B}^* = 2\bar{\mathrm{B}}_\Lambda({}_{\Lambda}^{3}\mathrm{H}) + \Delta\mathrm{B}_{\Lambda\Lambda}$ is the close to the full binding energy of the Λ pair in ${}_{\Lambda\Lambda}^{4}$H. These relations exhibit the dependence of the measured meson momentum on the combined resonance energy and $\Lambda\Lambda$ interaction energy.

The indefiniteness in the measured π_L momentum [4] subjects the pairing energy to some uncertainty. For example, with $\epsilon_R = 1.18$, lowering k^* by 300 keV results in $\Delta B_{\Lambda\Lambda} = 0.55$ MeV, while a corresponding increase in k^* yields 0.17 MeV.

One very interesting feature of these estimated values for $\Delta B_{\Lambda\Lambda}$, say 0.34 MeV, is the momentum for the truly two body decay to ${}^4_\Lambda$He(1^+). A similar approximation to that in Eq. (10) yields, with *no* ϵ_R involvement, $k_\pi = 116.5$ MeV/c. Such a line, although still consistent with the observed broad peak near 115 MeV/c, should be relatively easy to separate, in an improved resolution experiment, from the known 114.3 MeV/c pion from the decay of ${}^3_\Lambda$H (see Eq. (5)). Finding this peak in the π^-_H spectrum would provide more transparent evidence for the existence of ${}^{\;\;4}_{\Lambda\Lambda}$H.

In conclusion, we see that the existence of states above threshold in ${}^3_\Lambda$H + proton system can straightforwardly describe the narrow, low momentum, π^- feature at $104 - 105$ MeV/c observed in the BNL experiment E906. An argument in favor of such resonances is that a common average particle-cluster potential can be used to describe the gross structure of both the ground-state doublet of ${}^4_\Lambda$He and the negative-parity resonances.

The inferred energy of the resonance and energy range possible for $\Delta B_{\Lambda\Lambda}$, the latter likely somewhat less than 0.5 MeV, are not unreasonable. Takahashi *et al.* [3] found $\Delta B_{\Lambda\Lambda} = 1.0 \pm 0.38$ MeV for ${}^{\;\;6}_{\Lambda\Lambda}$He. One certainly expects a smaller value for the more extended mass 4 system. Only future experiments with better statistics and better resolution can settle this issue. Follow up experiments are awaited. It is encouraging that all theoretical 4-body S=-2 calculations to date center on a weakly, bound or unbound, state and that two [11–13], one a variational calculation, produce weak binding.

Experiment E906 has pointed to the existence of two interesting nuclides, both mass 4 objects, one a very light $S = -2$ hypernucleus, the other an unusual, if not completely unexpected, resonance in an $S = -1$ daughter nucleus. Finally, one can also infer a possible binding of less than 1.0 MeV for the highly elusive H-dibaryon [17]. Production of this object is severely reduced by the strong likelihood of a repulsive core in the $\Lambda\Lambda$ interaction [18]. Certainly the almost constant, large, 4.5 MeV claimed in early emulsion experiments must be abandoned, as must the existence of a hybrid H within nuclei incorpotating interesting behaviour at short $\Lambda - \Lambda$ separations [18].

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